The Use of Material Parameters Derived from the Impedance Spectroscopy as a New Diagnostic Method for the Evaluation of Root Canal Treatment

Impedance Spectroscopy Parameters Used in Dentistry

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Abstract

By means of the use of impedance spectroscopy to evaluate teeth material parameters applied to diagnose the root canal treatment, the aim of the work was to investigate whether the correlation exists among teeth material parameters such as: dielectric coefficient, electric resistance, teeth capacitance and volume fraction of root canals. Such correlation will enable the use of electrical impedance spectroscopy as a novel non-invasive method to estimate the number of unfilled canals before and during endodontic teeth treatment. For the studies, the impedance spectroscopy was used for the set of incisors, canines, premolars, and molars. The method involves application of a sinusoidally varying voltage and the measurements of the ensuing current flowing through the tooth placed in the saline solution. For each of the teeth studied, six independent impedance measurements were done.

It was shown that filling of the succeeding root canals resulted in an increase in the electrical resistance of the teeth. Correlation has been found among teeth capacitance, electrical resistance, dielectric coefficient and volume fraction of root canals; the latter parameter depending on the number of root canals and their structure. As indicated from the statistical analysis of the data obtained using the Cochran-Cox statistic, particularly the value of dielectric coefficient, which is the teeth material characteristic parameter, is an excellent indicator of the completion of root canals filling. It has been demonstrated that the result of impedance parameters can attest the presence of unfilled root canals.

Keywords

Impedance Spectroscopy; Electrochemistry; Polarization; Caries Diagnosis; Endometry; Dental Materials

Introduction

The term impedance spectroscopy (IS) has occurred in the English language reports proposed by chemists and physicists dealing with electrochemical problems, especially stable electrolytes, called heterogeneous systems in electrical engineering. [Morucci et al., 1996] One of the possibilities is impedance spectroscopy which has been successfully used to study electrical resistance of the healthy and carious teeth [Alwas-Danowska, 2007; Huysmans et al., 1996, 1998; Long bottom et al., 1996; Ricketts et al., 1997; Mosahebiand et al., 2002] and its temperature dependence [Huysmans et al., 2000], evaluation of filling ability of different dentist materials [Huysmans et al., 2000], as well to measure precisely root length using impedance endometry [Mayeda, 1993; Meredith et al., 1997; Pagavino et al. 1998; Steffen et al., 1999]. Variety of other properties of teeth has also been evaluated using electrical measurements [Junge et al., 1998; Meredith et al., 1997; Sim et al, 2001; Schulte et al., 1998; Wolinsky et al., 1999].

Recently, it is more frequently used in dentistry to evaluate the structures of dental materialsi.g.titanium corrosion [Alwas-Danowska, 2007; Barăo et al., 2001].

The results of studies carried out by Villat and coworkers in which impedance spectroscopy (a novel method to characterize the setting reaction) was app lied have appeared to be of great importance in assessment of the setting process of the dental materials studied. It was thought regarding the studies of cements and concrete that impedance spectroscopy may characterize ion mobility, porosity and setting processes of hydrogel dental materials. However, every method of using IS in relation to teeth should consider a complex heterogeneous structure of dental tissues (6.8 -7.0 in Moscha scale–e.g. enamel to soft tissues-the pulp–containing among others blood vessels or lymphatic vessels) [Villat et al., 2010].

There is also a necessity to design a quick and noninvasive method that will enable the assessment of not only the length, but the number of filled canals, prior to and following the endodontic treatment. The top aim of endodontic treatment is to extirpate the infected pulp, necrotic material and pathogens in the pulp cavity (pulp chamber and the root canals). Failures in endodontic treatment can then result from untreated canals or those that have not been found. According to Kersten (and other authors) incompletely filled or sealed canals are not usually the cause of pain complaints, however, unfilled canals or left untreated because they have not been detected may induce pain due to the pulp irritation, inflammation or necrotic state [Kersten et al., 1985]. This is confirmed by numerous clinical observations. As far as the evaluation of the real length of the canal is concerned, what does not pose a serious problem as it can be determined with the use of direct currents endometers and dental radiographs [Hör et al., 2005; Pagavino et al., 1998; Steffen et al., 1999]. However, detection and localization of the accessory canals do pose a great problem.

So far, the number of dental root canals has been assessed based on the statistical mean (depending on the tooth type) and the radiographic examination. This, however, often differs from *a priori* assumptions and must be additionally confirmed during root canal treatment. For the first time, the use of impedance spectroscopy to assess the extensiveness of internal structures of molar teeth was presented at the IDR Conference in Gőteborg [Alwas-Danowska et al., 2003; Alwas-Danowska et al., 2007].

This study presents the results of investigations considering parameters of impedance spectroscopy in relation to one-, two- or three-rooted teeth.

Materials and Methods

The impedance spectroscopy studies have been performed with the use of ATLAS HI device; and 108 measurements were done on the 38 canals, in 18 teeth removed for the orthodontic reasons. The set included 10 premolars, 5 molars, 2 incisors and 1 canine.

The data were grouped separately for teeth with one root canal (prior to the endodontic treatment) (group A), two canals (group B) and three or more canals (group C). Data studied were used for statistical analysis- see Table 1.

Impedance measurements were performed in a specially designed cell shown in Figure 1. We have done the measurements in the frequency range from 100 kHz to 1 Hz and stored the extracted teeth in an aqueous NaCl solution (NaCl concentration equal to 0.09 mol/kg); corresponding to the saline solution. To avoid possible errors resulting from the temperature and salt concentration dependence, electrical resistance of 5 aqueous solutions of NaCl (salt concentration from 0.09 to 0.2mol/kg) has been measured in the temperature ranging from 25 to 40^{o}C. The observed differences were negligible compared to the teeth resistances measured.

In impedance spectroscopy experiments, the working electrode in the form of a stainless steel needle, was placed inside the root canal. The reference electrode in the form of a stainless steel disc (surface area 0.57 cm^2) was placed directly under the tooth. The entire assembly was immersed in the saline solution. The outer tooth surface (not in the saline solution) was thoroughly dried before impedance experiments to avoid the formation of conductive surface pathways. The experiments were performed in the frequency range from 100 kHz to 1 Hz at 25℃ using Solartron Schlumberger 1255 FRA analyser coupled with EG&G 273A potentiostat. The method involves application of a sinusoidally varying voltage and the measurements of the ensuing current flowing through the tooth placed in the saline solution. For each of the teeth studied, six independent impedance measurements were done. The estimated error in the evaluation of electrical resistance was equal to 15-20%. The data were analysed by non-linear least square fitting using EQ 4.51 Boukamp package [Boukamp, 1986].

The electrical response of the material can be represented by an equivalent circuit consisting of parallel and (or) series combination of resistors and frequency dependent capacitors. In our experiments, the equivalent circuit comprises the parallel

combination of a bulk resistor and a frequency dependent geometrical capacitor (describing bulk properties of the tooth in the saline solution) in series with a frequency dependent double layer capacitor (describing properties of electrode-electrolyte interface). The impedance of the frequency dependent capacitors (often called constant phase element (CPE)) is calculated on the basis of the following equation

$$Z_{(CPE)} = C_o (j\omega/\omega_o)^n$$

Where C_o (geometrical (C_g) or double layer (C_{dl}) capacity, n- dielectric coefficient in the case of equation describing geometrical capacity frequency dependence which depicts the ideality of capacitor filled with particular material characterized by it [Jonscher, 1983]; for an ideal capacitor n=1, ω – frequency of the impedance measurements, ω_o- frequency for each type of the relaxation processes.

The volume fraction of root canals was estimated from gravimetric experiments by weighting the tooth after soaking in the saline solution and after thorough drying to the constant weight in an oven. Data studied were used for statistical analysis as indicated from the statistical analysis of the data obtained using the Cochran-Cox statistic.

Results

Mathematical analysis of the results show that the electrical resistances obtained for untreated teeth from group A and C are statistically different from each other. It was, however, statistically impossible to distinguish between teeth from group A and B. The teeth from group B and C are statistically distinguishable but due to the low number of teeth from group C the significance of this difference is low (for the details of the statistical analysis of the teeth resistance see Table 2).

Figure 2 shows radiophotographs of teeth used in the *in vitro* studies. A number of canals have been estimated based on these photographs. The average number of canals estimated is 2 for premolars, 1 for canine and incisors and ≥3 for molar teeth. We have subjected each of the studied teeth to impedance experiments.

The evolution of the impedance spectra upon progressive filling of teeth is shown in Figure 3 for the molar tooth denoted as the sample 15 in Figure 2. The Nyquist representation of the impedance data depicted on the complex plane consists of a low frequency spike and high frequency depressed semicircle. The spike is related to the electrode-electrolyte interfacial processes and vanishes when filling progresses. The high frequency semicircle represents bulk properties of the tooth in the NaCl solution and builds upon progression of endodontic treatment. This results from an increase in the electrical resistance of the sample, which changes its nature from ion conductor to dielectric.

In Figure 4, we have shown the changes in the electrical resistance (a), geometrical capacitance (b) and dielectric coefficient (c) as a function of the volume fraction of root canals in the tooth examined. Generally, electrical resistance and dielectric coefficient decrease with an increase in the volume fraction of root canals whereas the geometrical capacitance increases. These trends confirm an increase in the electrical resistance upon filling connected with the more dielectric nature of the filled teeth.

The representative impedance results have been summarised in Table 1 and confirmed data shown in Figures 3 and 4. The statistical analysis was performed for all the data obtained. The results of the analysis of the variation of teeth electrical resistance and dielectric coefficient for all teeth studied are included in the supplementary web material.

Upon partial filling of teeth, the differences in electrical resistances depend on the volume fraction of root canal in the tooth but not specifically on the number of unfilled canals. This most probably results from the different shape and volume of each canal, which is additionally randomly filled during endodontic treatment (see changes of R in Table 1 for various samples). As shown in Figure 4 linear correlation exists among the impedance parameters (electrical resistance, geometrical capacitance, and dielectric coefficient) and volume fraction of root canals in teeth. The experimental errors calculated for the evaluation of electrical resistance, geometrical capacitance and dielectric coefficient are roughly equal to 15%, 30% and 3%, respectively (these errors were estimated on the basis of impedance measurements performed for each sample). Errors obtained for capacity evaluation from impedance spectra are sometimes greater than those estimated for impedance measurements. As indicated in Figure 4, as well the electrical resistance data exhibit scattered characteristic due to the fact that the use of electrical resistance as an evidence of the completion of endodontic treatment might sometimes be problematic.

Discussion

The use of dielectric coefficient which describes the ideality of capacitor filled with particular material

characterised by it, proves to be extremely useful for teeth which visually look like filled ones but for which dielectric coefficient values are considerably below 0.84. Taking as an example, the molar tooth denoted as sample 12 in Table 1 and sample 12 on Figure 1, the visual observation suggests the presence of 3 root canals. However, after filling procedure, the final n value is equal to 0.69±0.03 (see Table 1), which suggests the presence of an additional canal or division of one of already established canals. The sectioning performed after completion of impedance spectroscopy experiments proves the presence of the four-canal structure. Similar suggestions have been proved for other teeth for which the final dielectric coefficient value was considerably lower than 0.84. It should be emphasised that dielectric coefficient values are much sensitive to changes of the shape and volume of root canals which are additionally randomly filled during endodontic treatment compared to teeth resistance which was so far more extensively use in dental diagnosis [Ashley, 2000; Attril, 2001]. This is confirmed by the statistical analysis (see Table 3) showing that there is no statistical difference between dielectric coefficients obtained at stage 2 for the teeth from group A and at stage 3 for the teeth from group B. In both cases, all root canals were filled and closed. On the other hand, the same analysis shows statistical difference in n values between filled and partially filled teeth (see stage 2 for group A and stage 3 for group B in both in comparison to stage 4 group C teeth). Therefore, it is strongly suggested to use a value of the dielectric coefficient n (for which calculated errors are the lowest) as a proof of the completion of filling procedure.

To conclude, the results of the investigations have confirmed that the kinds of the tooth have the great influence on the results of the studies in caries diagnosis (what was earlier described by some authors in relation to the degree of tooth growth [Ashley, 2000; Attril, 2001]. The implementation of this method would allow for reduction of pain complaints following inadequately filled root canals and also reduction of potential centres of infection. To take into consideration the frequency and high prevalence of these complications, application of this new method is very important. The presented laboratory results can easily be transferred to *in vivo* studies using the equipment similar to this used in endometry to measure the length of a root. In these *in vivo* studies ac current should be applied in the frequency range sufficient for the calculation of dielectric coefficient.

Moreover, the accuracy of impedance spectroscopy is considerably higher than that for radiographic studies which additionally involve undesirable exposure to ionizing radiation.

It has been demonstrated that the result of impedance parameters can attest the presence of unfilled root canals.

Conclusion

One need to keep in mind that in the case of the application of impedance spectroscopy in clinical dentistry treatments, always the anatomical differences between particular types of teeth have to be considered since they might have important effect on endodontic treatment as well as the structure of dental materials used.

Taking into consideration of this parameter may facilitate the determination of the real grade at the caries diagnosis precisely.

REFERENCES

Alwas-Danowska, Hanna M. „The Performance of Electrical Conductance and Laser Fluorescence Measurements in the Diagnosis of Incipient Approximal Caries Lesions – a Histological Validation." Polish Journal of Environmental Studies 16 (2007): 232-5.

Alwas-Danowska,Hanna M. et al. "The Use of Impedance Spectroscopy for the Evaluation of Root Canal Treatment." Polish Journal of Environmental Studies 16 (2007): 515-8.

Alwas-Danowska, Hanna M. et al. "Can Electrical Impe dance Measurements Predict the Presence of Unfilled Root Canals During Root Canal Treatment? " Journal of Dental Researches 82 (2003): B263.

Ashley, Paul et al. "Predicting Occlusal Caries Using the Electronic Caries Monitor." Caries Research 34 (2000): 201-3.

Attrill, David and Paul Ashley. "Occlusal Caries Detection in Primary Teeth: a Comparison of DIAGNOdent® with Conventional Methods." British Dental Journal 190 (2001): 4.

Barăo, Valentin A. et al. „The Role of Lipopolysaccharide on the Electrochemical Behavior of Titanium". Dental Research 90 (2011): 613-8.

Boukamp, Bernard A. "A Package for Impedance/admittance Data Analysis". Solid State Ionic s 18/19 (1986): 136-40

Hör, David et al. "Ex Vivo Comparison of two Electronic

Apex Locators with Different Scales and Frequencies". International Endodontic Journal 38 (2005): 855-9.

Huysmans, Mary C. et al. "Temperature Dependence of the Electrical Resistance of Sound and Carious Teeth." Journal of Dental Research 79 (2000): 1464-8.

Huysmans, Mary C. et al. "Surface-specific Electrical Occlusal Caries Diagnosis: Reproducibility, Correlation with Histological Lesion Depth, and Tooth Type Dependence." Caries Research 32 (1998): 330-6.

Huysmans, Mary C. et al. "Impedance Spectroscopy of Teeth with and without Approximal Caries Lesions – An in vitro Study." Journal of Dental Research 75 (1996): 1871-8.

Jacquot, Bernard M. et al. "Mickroleakage of Cavit, CavitW, CavitG, IRM by Impedance Spectroscopy." International Endodontic 29 (1996): 256-61.

Jonscher, Alfred. Dielectric Relaxation in Solids, Chelsea Dielectric Press, London 1983.

Junge, Thomas et al., "Load Fatigue of Compromised Teeth: A Comparison of 3 Luting Cements." International Journal of Prosthodontics 11 (1998): 558-64.

Kersten, Harries and S. Thoden van Velzen. "Electronic Canal Length Determination. A Clinical Valuation of the Neosono". Journal Art., 92 (1985): 58-60.

Longbottom, Christopher et al. "Detection of Dental Decay and its Extent Using AC Impedance Spectroscopy." Natural Medicine 2 (1996): 235-7.

Mayeda, David L. et al. "In vivo Measurement Accuracy in Vital and Necrotic Canals with the Endex Apex Locator." Journal of Endodontic. 19 (1993): 545-8.

Meredith, Neil and Kishor Gulabivala. "Electrical Impedance Measurements of Root Canal Length," Endodontic Dental Traumatology 13 (1997): 126-31.

Meredith, Neil and Derrick J. Setchell. "In Vitro Measurements of Cuspal Strain and Displacement in Composite Restored Teeth". Journal of Dentistry 25 (1997): 331-7.

Morucci, Jerry et al. "Matrix Determination for In Vivo Tissue Characterization by Parametric Electrical Impedance Imaging". Annual International Conference of the IEE Engineering in Medicine and Biology, 1996, Proceedings, v 2.

Mosahebi, Negin and David N. Ricketts. "Effect of Contact Media on the Diagnostic Quality of Electrical Resistance Measurements for Occlusal Caries." Community Dental Oral, 30 (2002): 161-7.

Pagavino, Gonsalves et al. "A SEM Study of In Vivo Accuracy of the Root ZX Electronic Apex Locator." Journal of Endodontic 24 (1998): 438-41.

Ricketts, David N. et al. "The Effect of Airflow on Site-specific Electrical Conductance Measurements Used in the Diagnosis of Pit and Fissure Caries In Vitro." Caries Research 31 (1997): 111-8.

Schulte, Alfons et al."Post Eruptive Changes of the Electrical Resistance Values in Fissure Enamel Premolars."Journal of Dentistry 26 {1998): 113-18.

Sim, T. P. et al. "Effect of Sodium Hypochlorite on Mechanical Propel-ties of Dentine and Tooth Surface Strain." International Endodontic Journal, 34 (2001): 120-32.

Steffen, Heike et al. "Comparison of Measurements Obtained With Hand Files or Canal Leader Attached to Electronic Apex Locators: in Vitro Study. International Endodontic 32 (1999): 103-7.

Villat, C. et al., „Impedance Methodology: A New Way to Characterize the Setting Reaction of Dental Cements." Dental Material 26 (2010): 1127-32.

Wolinsky, Lauren E. et al. "An in Vitro Assesement and Pilot Clinical Study of Electrical Resistance of Demineralized Enamel" Journal Clinical Dental 10 (1999): 40-3.

TABLE 1 IMPEDANCE PARAMETERS FOR THE TEETH STUDIED

P- PREMOLARS; M – MOLARS; C – CANINE ; I- INCISORS;

R- BULK RESISTANCE OF THE TOOTH IN THE SALINE SOLUTION;

CPE- CONSTANT PHASE ELEMENT (PSEUDO-GEOMETRICAL CAPACITY)

N- DIELECTRIC COEFFICIENT

M- VOLUME FRACTION OF ROOT CANALS

STAGE I – UNTREATED TEETH

STAGES II-IV SHOW IMPEDANCE DATA DURING THE PROGRESSION OF ENDODON*TIC TREATMENT*

Group A

Sample number		**3**	**7**	**8**	**9**	**10**	**17**	**18**
Tooth's type		**c**	**I**	**i**	**p**	**p**	**p**	**p**
R/Ω	**STAGE I**	2,17e4	2,17e4	1,56e4	2,31e4	1,02e5	2,76e4	3,15e4
	STAGE II	5,05e5	3,2e6	4,12e5	5,42e4	9,01e5	4,65e6	9,42e6
	STAGE III		-	-	-	-	-	-
CPE/Fcm^{-2}	**STAGE I**	2,59e-8	4,36e-9	1,69e-8	4,22e-11	1,16e-9	2,14e-9	4,67e-10
	STAGE II	1,49e-11	2,84e-11	5,21e-11	5,79e-10	3,69e-11	2,47e-11	2,14e-11
	STAGE III		-	-	-	-	-	-
n	**STAGE I**	0,49	0,62	0,54	0,71	0,65	0.64	0,74
	STAGE II	0,96	0,91	0,87	0,9	0,89	0,91	0,91
	STAGE III		-	-	-	-	-	-
M/vol/vol	**STAGE I**	0,097	0,098	0,096	0,141	0,91	0,048	0,041
	STAGE II	0,053	0,066	0,07	0,126	0,88	0,023	0,033
	STAGE III		-	-	-	-	-	-

Group B

Sample number		**1**	**2**	**4**	**5**	**6**	**11**	**12**
Tooth's type		**p**	**M**	**p**	**p**	**p**	**p**	**m**
R/Ω	**STAGE I**	3,87e4	7,76e3	1,32e3	2,36e4	3,06e4	5,06e2	8,46e3
	STAGE II	6,83e4	2,90e4	2,25e4	4,22e4	4,28e5	3,30e3	1,53e4
	STAGE III	1,32e5	4,76e4	2,93e4	2,56e5	1,53e6	1,73e6	8,94e4
CPE/Fcm^{-2}	**STAGE I**	1,14e-8	7,41e-8	-	3,19e-8	9,11e-9	-	2,88e-7
	STAGE II	3,32e-11	1,62e-10	3,91e-9	1,51e-9	5,92e-11	3,96e-6	8,51e-8
	STAGE III	3,07e-11	5,13e-11	1,07e-10	1,94e-11	2,64e-11	7,77e-11	8,5e-10
n	**STAGE I**	0,49	0,5	-	0,48	0,57	-	0,46
	STAGE II	0,87	0,81	0,62	0,65	0,87	0,29	0,47
	STAGE III	0,89	0,89	0,84	0,94	0,91	0,84	0,69
M/vol/vol	**STAGE I**	0,163	0,118	0,185	0,132	0,102	0,177	0,170
	STAGE II	0,145	0,082	0,101	0,127	0,1	0,173	0,131
	STAGE III	0,142	0,035	0,052	0,053	0,041	0,049	0,103

Group C

Sample number		14	15	16
Tooth's type		m	m	m
R/Ω	STAGE I	2,23e3	2,02e3	3,55e3
	STAGE II	4,07e3	2,19e3	5,05e3
	STAGE III	1,49e4	9,7e4	8,65e3
	STAGE IV	2,58e5	4,12e5	1,3e5
CPE/Fcm^{-2}	STAGE I	7,95e-8	1,11e-6	2,82e-7
	STAGE II	9,26e-9	-	2,44e-8
	STAGE III	9,06e-10	2,23e-10	1,28e-8
	STAGE IV	1,56e-10	5,32e-10	8,86e-10
n	STAGE I	0,53	0,33	0,43
	STAGE II	0,62	-	0,53
	STAGE III	0,74	0,69	0,56
	STAGE IV	0,79	0,71	0,69
M/vol/vol	STAGE I	0,165	0,147	0,086
	STAGE II	0,160	0,134	0,085
	STAGE III	0,161	0,097	0,08
	STAGE IV	0,052	0,02	0,034

TABLE 2 STATISTICAL ANALYSIS OF THE TEETH RESISTANCE

Stage Number		Group of Teeth Studied		
		A (7 teeth)	B(7teeth)	C (3 teeth)
I	x±s	3,47e4±3,01e4	1,79e4±1,36 e4	2,60e3±8,30e2
	Mediana	2,31e4	1,48e4	2,23e3
	Min-max value	1,56e4 – 1,02e5	1,32e3 – 3,87e4	2,02e3 – 3,55e3
II	x±s	2,73e6±3,40e6	9,43e4±1,48e5	3,77e3±1,45e3
	Mediana	9,01e5	4,22e4	4,07e3
	Min-max value	5,42e4 – 9,42e6	1,53e4 – 4,28e5	2,19e3 – 5,05e3
III	x±s		3,10e5±5,43e5	4,02e4±4,93e4
	Mediana		9,94e4	1,49e4
	Min-max value		2,93e4 – 1,53e6	8,65e3 – 9,7e4
IV	x±s			2,67e5±1,42e5
	Mediana			2,58e5
	Min-max value			1,30e5 – 4,12e5
Statistically important differences	Stage I-II p<0,003	Stage I-II p<0,04		
		Stage I-III p<0,005		

TABLE 3 STATISTICAL ANALYSIS OF THE DIELECTRIC COEFFICIENT (N)

Stage Number		**Group of Teeth Studied**		
		A (7 teeth)	B(7teeth)	C (3 teeth)
I	x±s	0,623±0.088	0,500±0,037	0,430±0,100
	Mediana	0,640	0,495	0,430
	Min-max value	0,490 – 0,740	0,460 – 0,570	0,330 – 0,530
II	x±s	0,907±0,028	0,723±0,157	0,575±0,064
	Mediana	0,910	0,740	0,575
	Min-max value	0,870 – 0,960	0,470 – 0,870	0,530 – 0,620
III	x±s		0,885±0,039	0,663±0,093
	Mediana		0,890	0,690
	Min-max value		0,840 – 0,940	0,560 – 0,740
IV	x±s			0,730±0,053
	Mediana			0,710
	Min-max value			0,690 – 0,790
Statistically important differences		Stage I-II p<0,001	Stage I-II p<0,02	
			Stage I-III p<0,001	Stage I-III p<0,001
			Stage II-III p=0,05	Stage I-IV p<0,002
Statistically important differences for the last stage of endodontic treatment	Group A (stage II) – Group C (stage IV) p<0,001			
	Group B (stage III) – Group C (Stage IV) p<0,002			

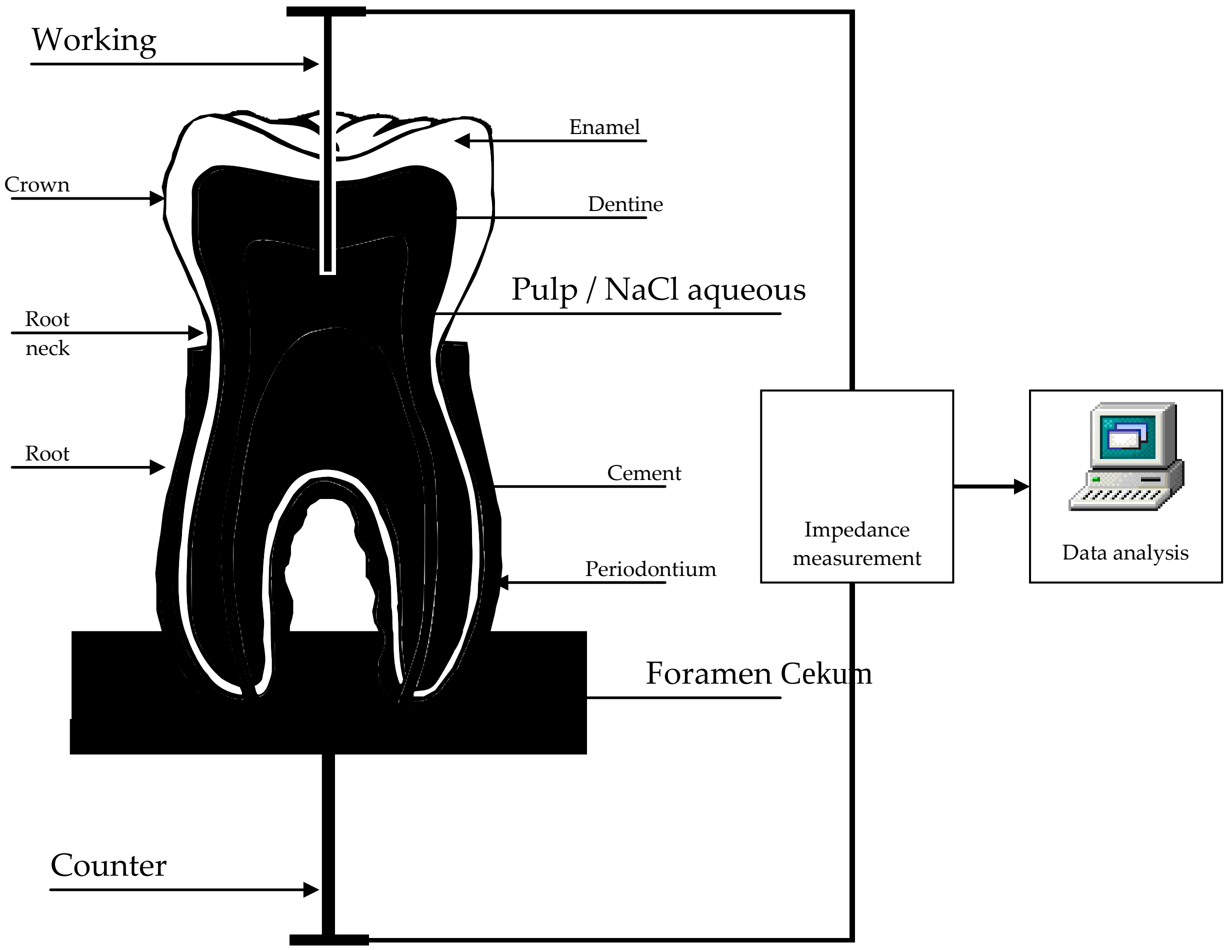

FIG. 1 SKETCH OF THE CELL USED FOR THE SPECTROSCOPY IMPEDANCE EXPERIMENTS

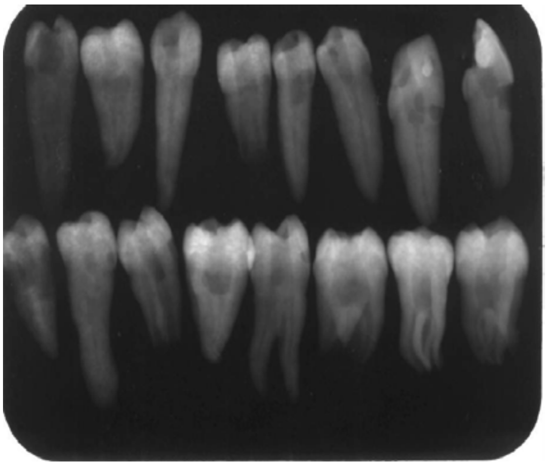

FIG. 2 RADIOGRAMS OF THE STUDIED TEETH UNDERTAKEN BEFORE ENDODONTIC TREATMENT. SAMPLES NUMBERED FROM 1 IN THE UPPER LEFT CORNER TO 16 IN THE LOWER RIGHT CORNER

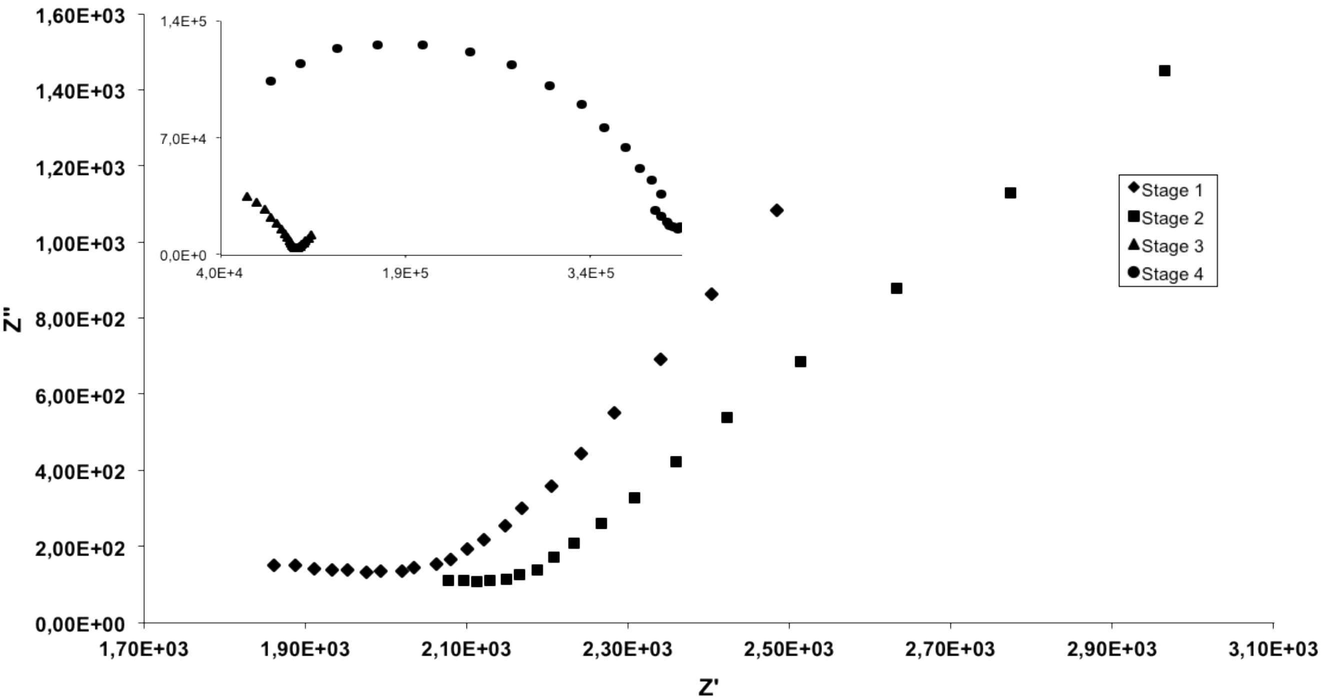

FIG. 3 CHANGES OF THE EXEMPLARY IMPEDANCE SPECTRA DEPICTED ON THE COMPLEX PLANE FOR THE SAMPLE NUMBER 15 DURING ENDODONTIC TREATMENT. STAGES 1 AND 2 ARE SHOWN ON THE MAIN PICTURE. STAGES 3 AND 4 ARE SHOWN AS AN INSERTION. DATA ON AXISES IN OHMS.

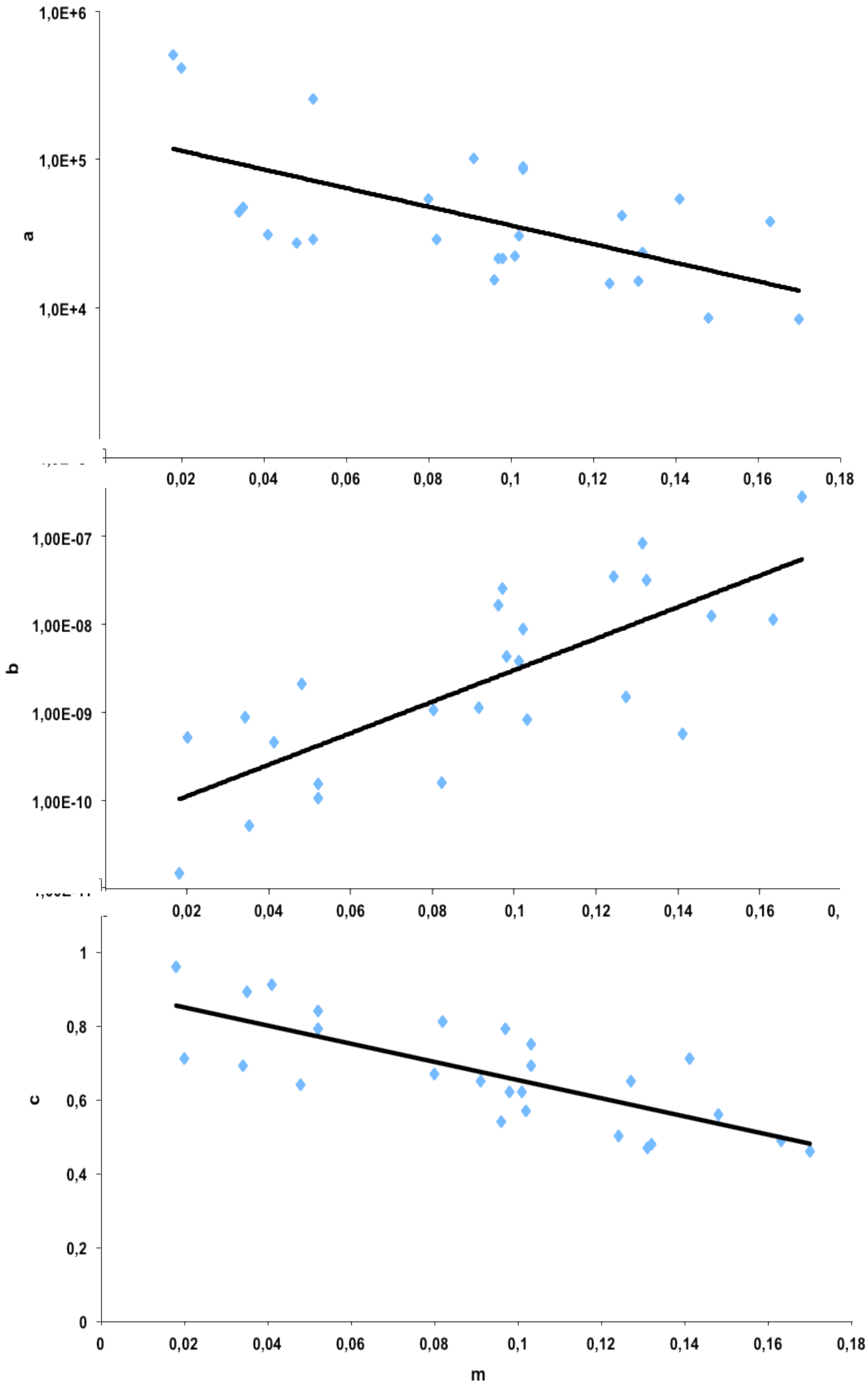

FIG. 4 CHANGES OF THE IMPEDANCE PARAMETERS (BULK RESISTANCE – R IN OHMS – a, PSEUDO-GEOMETRICAL CAPACITY - - CPE IN Fcm^{-2} -b, DIELECTRIC COEFFICIENT –n – c) AS A FUNCTION OF VOLUME FRACTION OF ROOT CANALS – m.